Neutrino Interactions and Long-Baseline Physics

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General Motivation

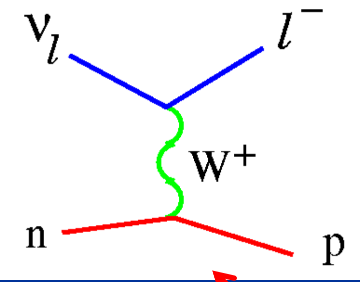
- Aspects of neutrino-nuclear reactions
  - Hadron physics:
    - axial couplings of nucleon resonances
    - reaction rates
  - Neutrino oscillation physics:
    - energy reconstruction

Neutrino Cross Sections: Nucleon

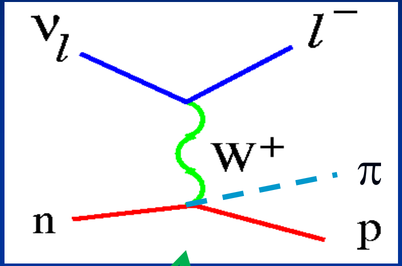
- Cross sections on the *nucleon*:
  - QE
  - Resonance-Pion Production + Born terms
  - Deep Inelastic Scattering → Pions, Kaons,...

Neutrino-nucleon cross section

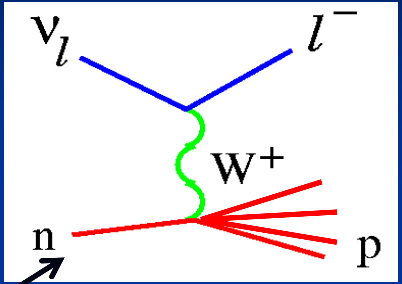
CCQE

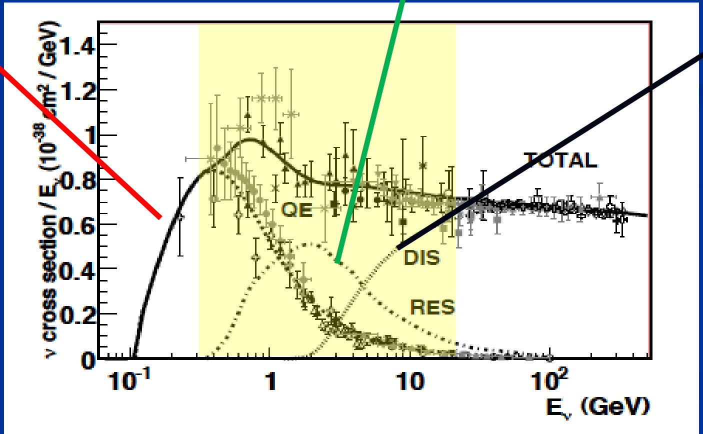


1π



DIS



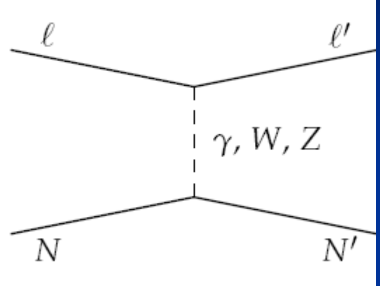


From: J.A. Formaggio, G.P. Zeller FNAL 05/15

note:
$10^{-38}\ \mathrm{cm}^2 = 10^{-11}\ \mathrm{mb}$

Yellow: energy range of present experiments

Quasielastic Scattering



- Vector form factors from *e* –scattering
- axial form factors

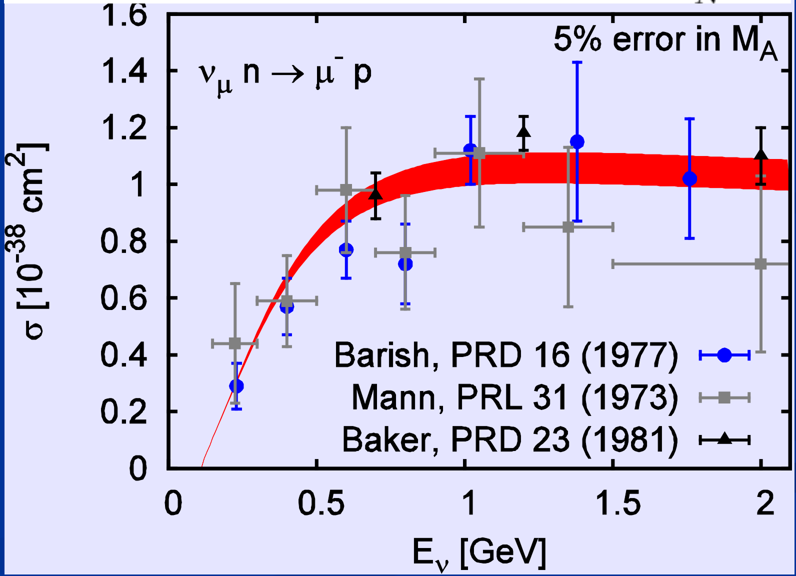
$F_A \Leftrightarrow F_P$ and $F_A(0)$ via **PCAC**

dipole ansatz for F_A with

M_A= *1* GeV**:**

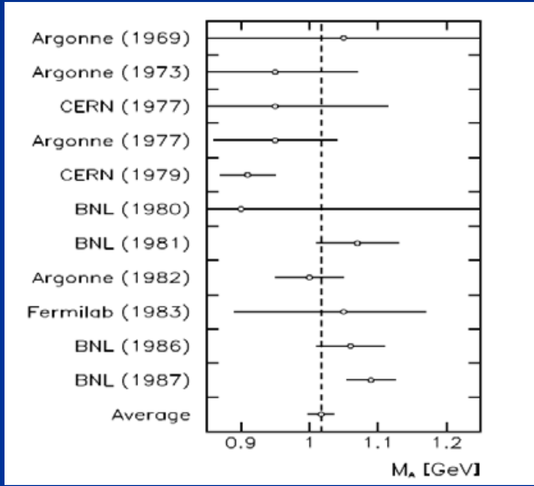
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

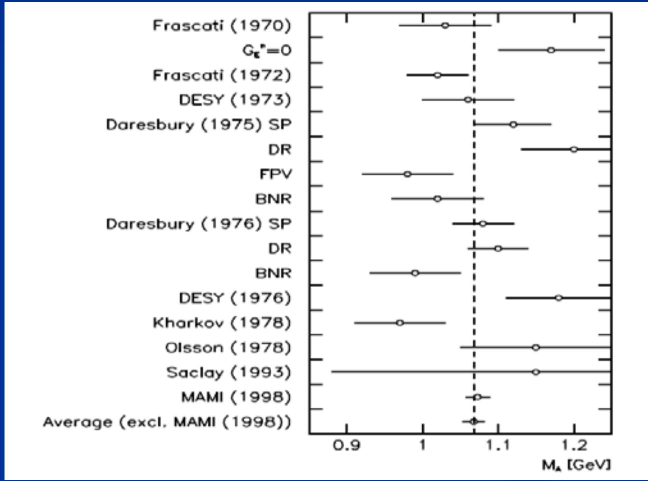
$$J^\mu_{QE} = \left(\gamma^\mu - \frac{\not{q}\, q^\mu}{q^2}\right) F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_\alpha F_2^V + \gamma^\mu\gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P$$



Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data





$M_A \cong 1.02$ GeV world average

$M_A \cong 1.07$ GeV world average

Dipole ansatz is simplification, not good for vector FF

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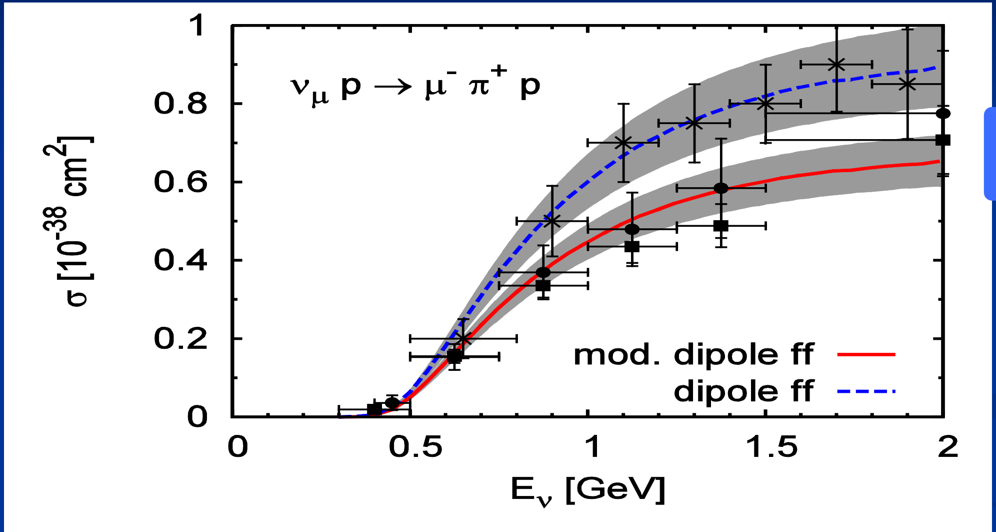
Pion Production

$$J^{\alpha\mu}_{\Delta} = \left[\frac{C_3^V}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu)\right]\gamma_5$$
$$+\frac{C_3^A}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2}q^\alpha q^\mu$$

- pion resonance production dominated by **P_{33}(1232) resonance**

- ***$C^V(Q^2)$*** from electron data (MAID analysis with CVC)
- ***$C^A(Q^2)$*** from fit to neutrino data (experiments on hydrogen/deuterium), so far only C^A_5 determined, for other axial FFs only educated guesses

Pion Production

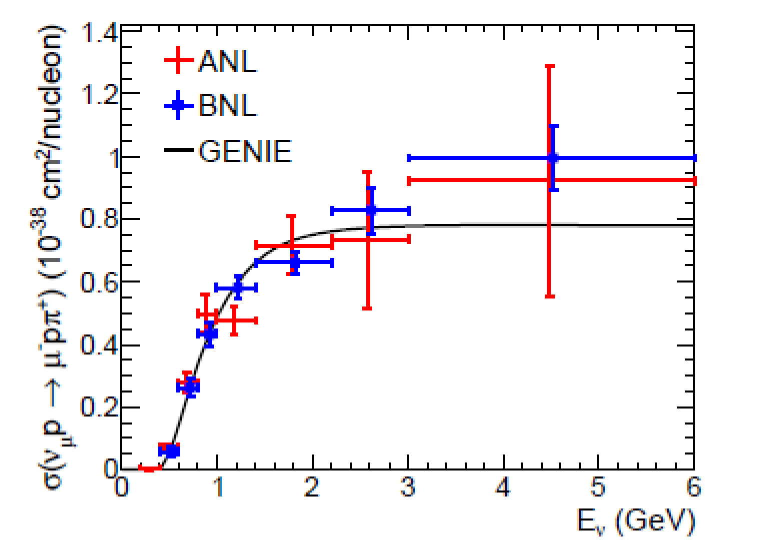


10 % error in $C_5^A(0)$

data:
PRD 25, 1161 (1982), PRD 34, 2554 (1986)

discrepancy between elementary data sets due to flux uncertainties (?)
→impossible to determine 3 axial formfactors

Pion Production



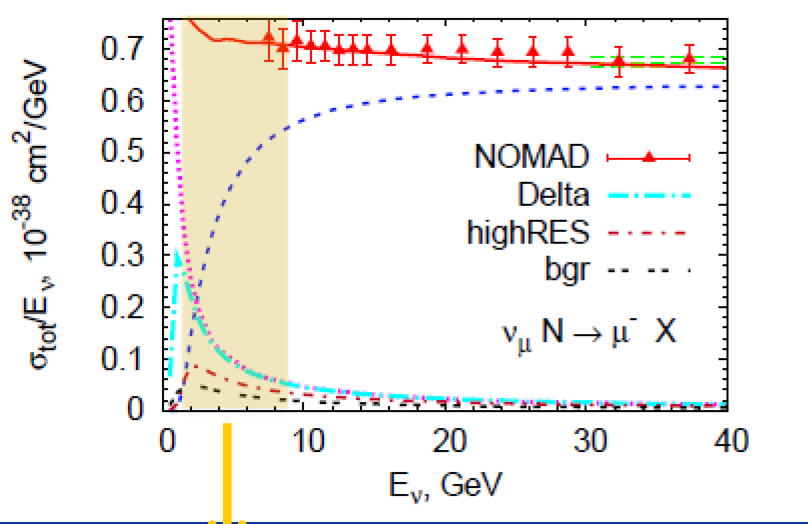
C. Wilkinson et al, PRD 90 (2014)

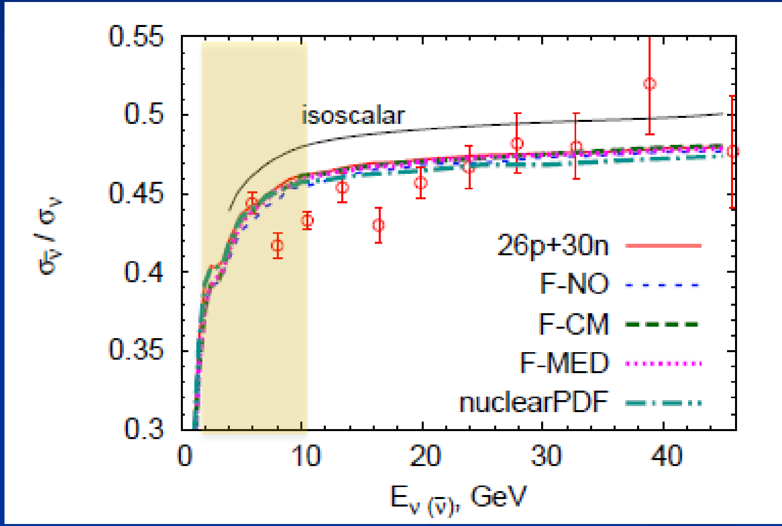
Reanalysis of BNL data (posthumous flux correction) by T2K group:
C.Wilkinson et al,
Phys.Rev. D90 (2014) 11, 112017

Agrees with earlier findings in
Graczyk et al, Phys.Rev. D80 (2009) 093001
Lalakulich et al, Phys.Rev. D82 (2010) 093001

One pion puzzle solved: ANL data preferable, but only C_5 determined:
BUT: extraction of p data from d data is doubtful (Sato et al)

Pions through SIS - DIS





Shallow Inelastic Scattering,
interplay of different reaction mechanisms

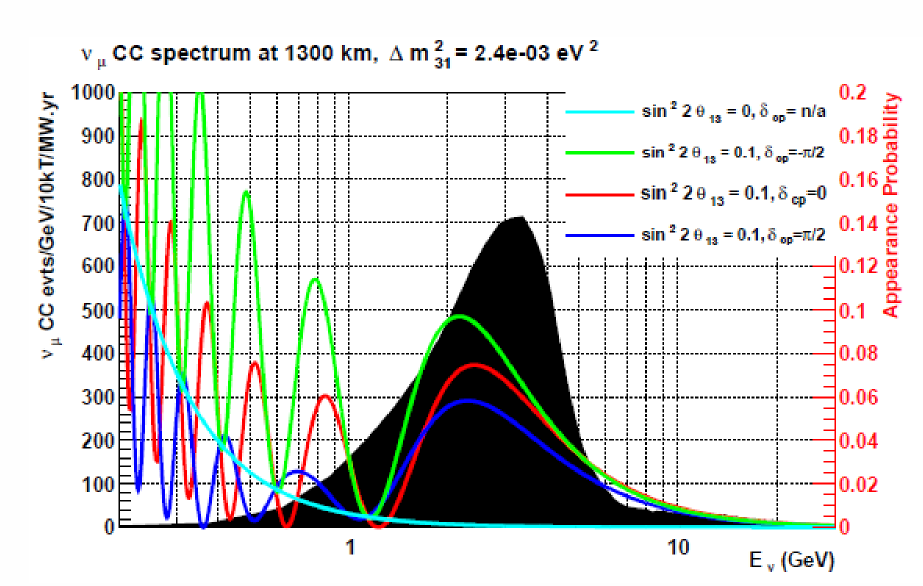
Curves: GiBUU

Calculated by string fragmentation models

Neutrino Oscillations

- State of affairs:
  - All mixing angles are known, with some errors
  - Mass hierachy not known
  - Possible CP violating phase not known
- All experiments use nuclear targets
- Errors determined by energy reconstruction:
  How well do we have to know the neutrino energy?

DUNE, δ_{CP} Sensitivity



Appearance probability:
$P_{\mu \rightarrow e}$

Need energy to distinguish between different δ_{CP}

Need to know neutrino energy to better than about 100 MeV

All Experiments use Nuclear Targets

Neutrino Cross Sections: Nucleus

- Cross sections on the *nucleon*:
  - QE + in-medium broadening
  - Resonance-Pion Production + reabsorption
  - Deep Inelastic Scattering → Pions + reabsorpt
- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., 2p-2h excitations

Nuclear Theory

- Necessary Ingredients
  - Nuclear groundstate (correlations, spectral functions)
  - Nuclear reaction mechanisms (IA vs. 2p2h, coll. excit.)
  - Electroweak interaction vertices, in medium
  - Particle production, also in secondary colls
  - Propagation of all particles to final state, incl fsi
- Only capable method: Transport Theory, guidance from QGP generators (MC is poor man‘s transport theory)

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** describes (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions
  - low and high energy photon and electron induced reactions
  - neutrino induced reactions

using the same physics input! And the same code!

NO TUNING!

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations

- Physics content and details of implemntation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
  Mine of information on theoretical treatment of potentials, collision terms, spectral functions and cross sections, useful for any generator

Transport Equation

Collision term

$$\mathcal{D}F(x,p) + \mathrm{tr}\left\{\mathrm{Re}\tilde{S}^{\mathrm{ret}}(x,p), -\mathrm{i}\tilde{\Sigma}^{<}(x,p)\right\}_{\mathrm{pb}} = C(x,p).$$

Drift term

$$\left[\left(1-\frac{\partial H}{\partial p_0}\right)\frac{\partial}{\partial t} + \frac{\partial H}{\partial \mathbf{p}}\frac{\partial}{\partial \mathbf{x}} - \frac{\partial H}{\partial \mathbf{x}}\frac{\partial}{\partial \mathbf{p}} + \frac{\partial H}{\partial t}\frac{\partial}{\partial p^0} + \text{KB term}\right] F(x,p)$$
$$= \text{- loss term} + \text{gain term}$$

$$F(x,p) = 2\pi g f(x,p) A(x,p).$$

Spectral function

Phase-space distribution

GiBUU Output

- GiBUU produces
  1. Full event file: four-vectors of all particles in final state
  2. 70.000 events per hour, on a PC, inclusive abououot 1 hour
  3. Events separated into 6 event classes, acc. to primary interaction, allows for reweighting
  4. Contains Analysis: Tens of cross sections, directly in Gnuplottable format: energy and angle differential
  5. Energy and Q^2 reconstruction files incl migration files
  6. Oscillation signal, both true and reconstructed

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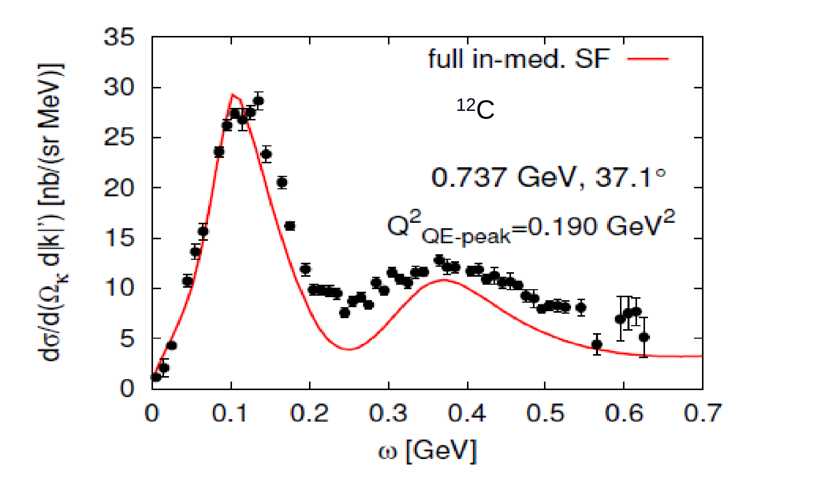
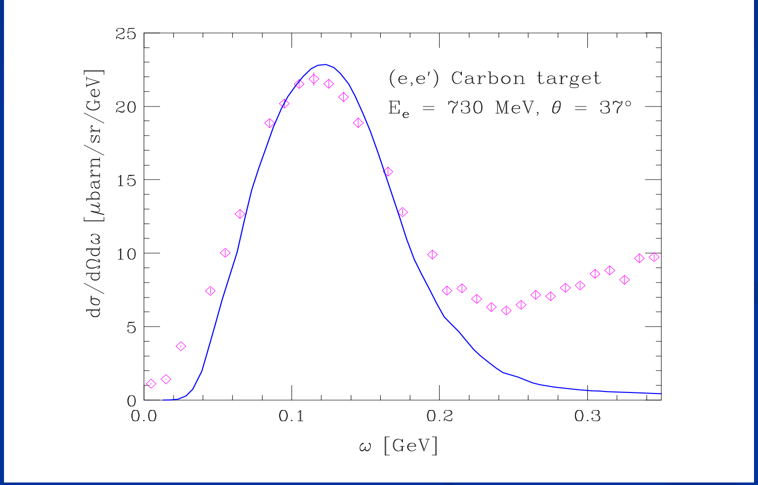
Test with electron data

Electrons as Benchmark for GiBUU

Trouble for neutrinos: ω must be reconstructed





No free parameters!
no 2p-2h, contributes
in dip region and under Δ

O. Benhar, spectral fctn

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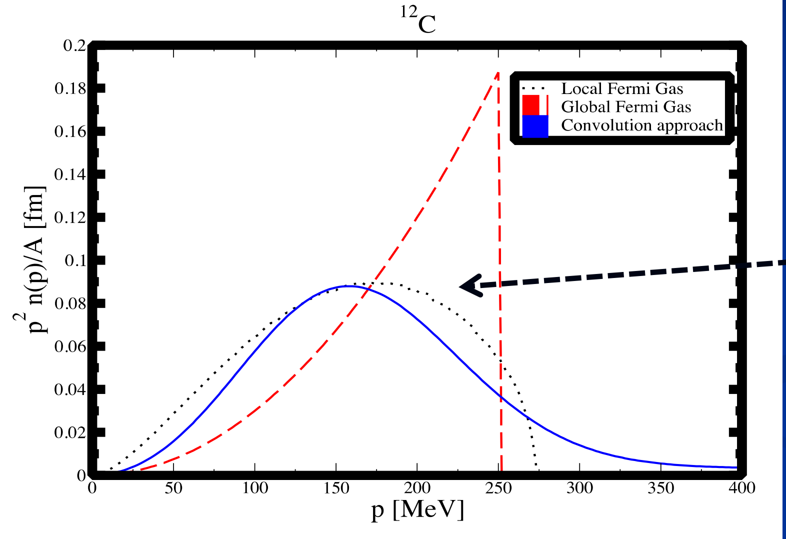
Momentum Distribution GiBUU

Alvarez-Ruso et al,
New J.Phys. 16 (2014) 075015



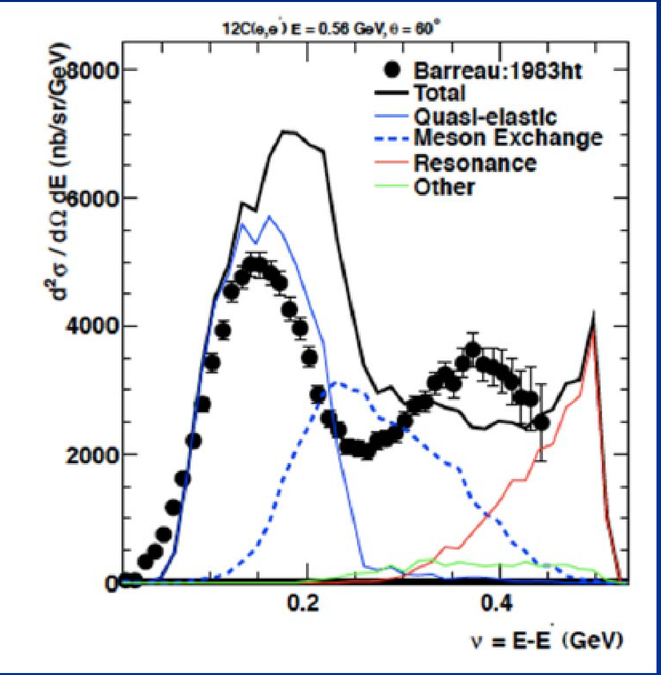
From: Alvarez-Ruso, Hayato, Nieves, arXiv:1403.2673

GiBUU uses
Local Fermi Gas
Energy-distribution smooth
because of r-dependent
potential

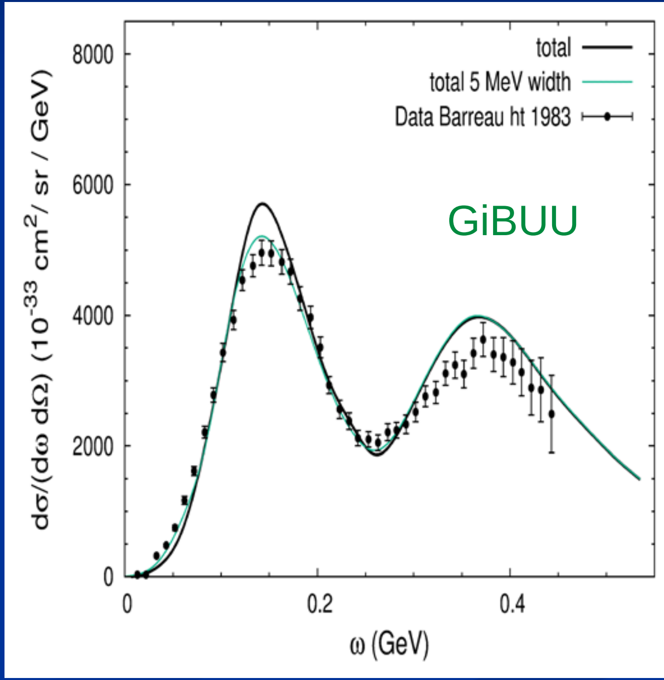
Same gs for all processes

$$P_h(\vec{p}, E) \propto \int d^3r\, [\Theta(p_F(\vec{r}) - p)\, \delta(E + T_p + V(\vec{r}, \vec{p}))]$$

GENIE vs GiBUU



GENIE, from S.Dytman, JLAB meet, May 2015



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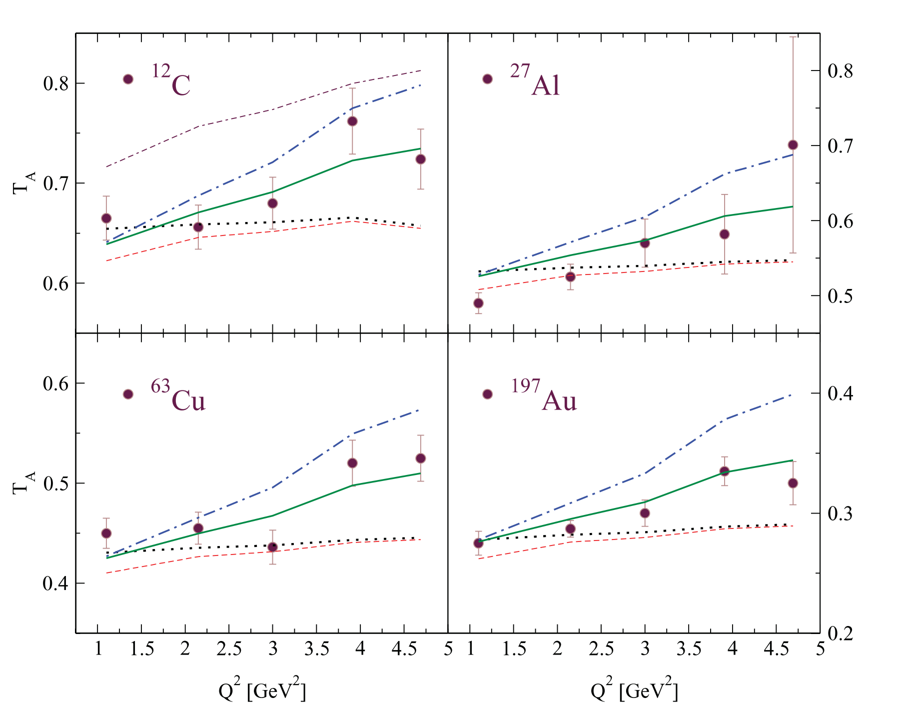
JLAB Pion Production

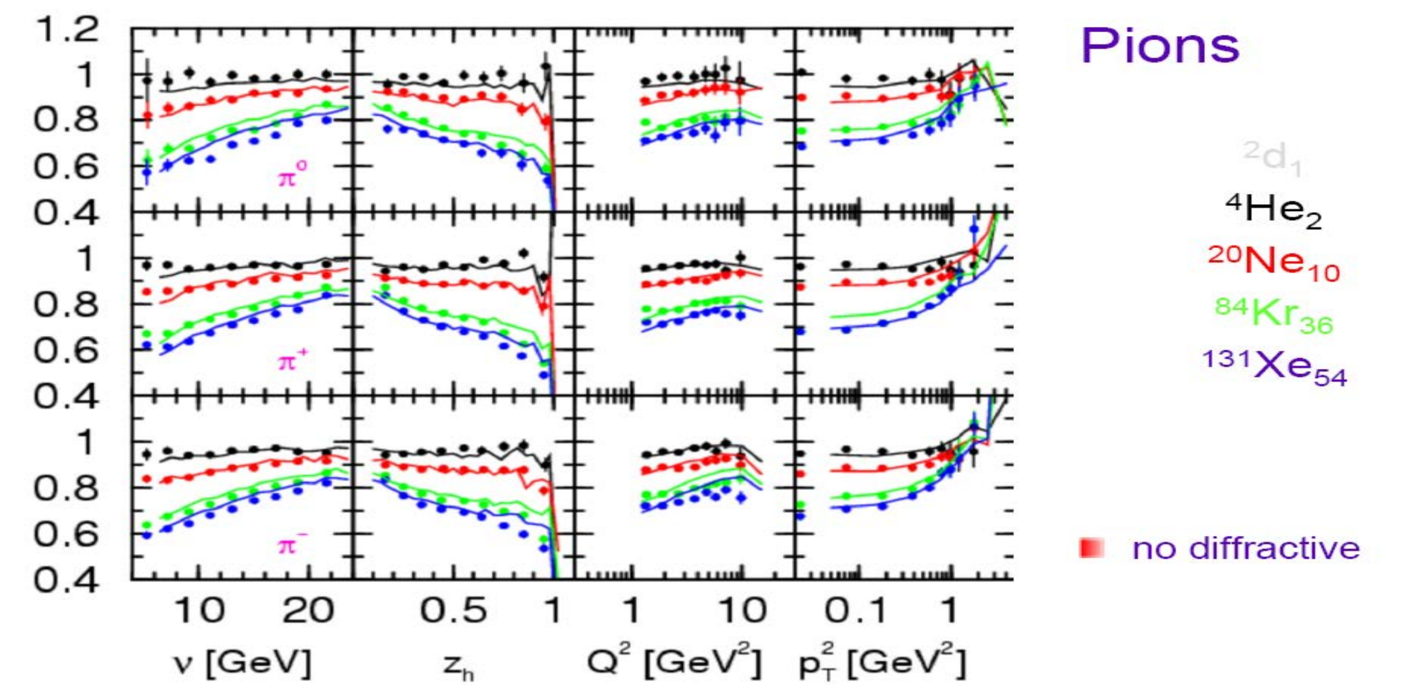


Exp: B. Clasie et al.
Phys. Rev. Lett. 99, 242502 (2007).

GiBUU: Kaskulov et al,
Phys.Rev. C79 (2009) 015207

HERMES@27 GeV and GiBUU

Airapetian et al.



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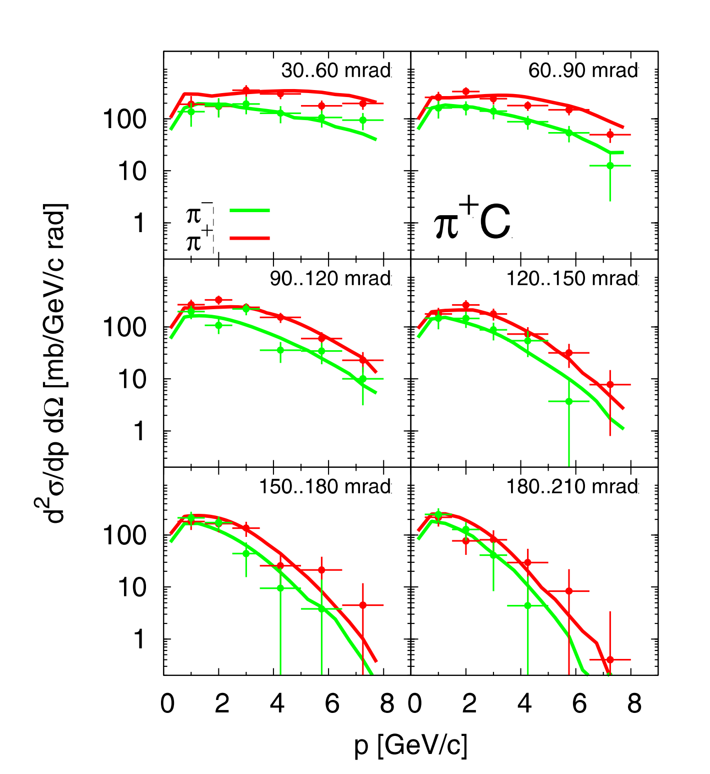
Check: pions in HARP

HARP small angle analysis
12 GeV protons

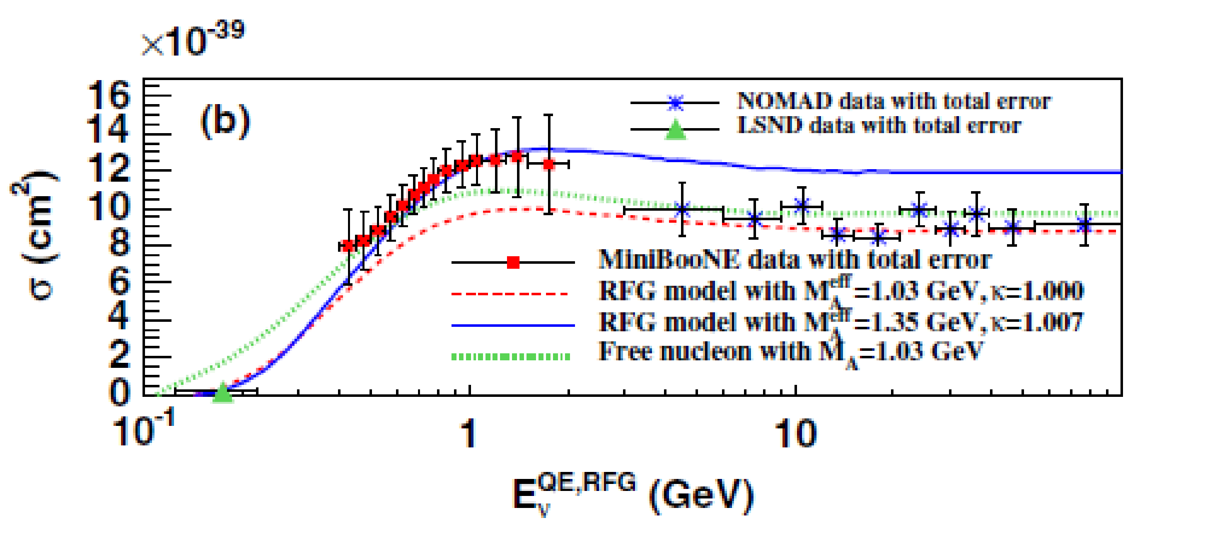
Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)



GiBUU simulates neutrinos from their birth to their death

M_A Puzzle

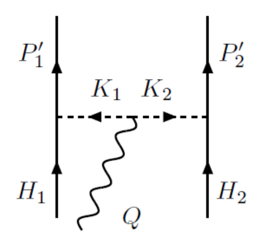


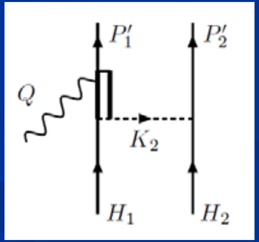
World average axial mass: M_A = 1.03 GeV, but MB data best fit by M_A ~ 1.35 GeV

Note: neither σ nor *E* are directly measured

M_A Puzzle

- K2K, MINOS and T2K also find large axial mass
- Accepted explanation: initial 2 particle interactions (2p2h), typical many-body effect (Martini et al., 2009), seen and explored in electron scattering since ~25 years





- Surprisingly, MINOS (2014!) and T2K (2014!) still use the one-particle model (1p1h, impulse approximation) to fit the data
- Fitting an unapplicable model (1p1h) to the data (2p2h) must yield unphysical parameters!

Pion Production

from: Phys.Rev. C87 (2013) 014602

1p-1h-1π X-section:

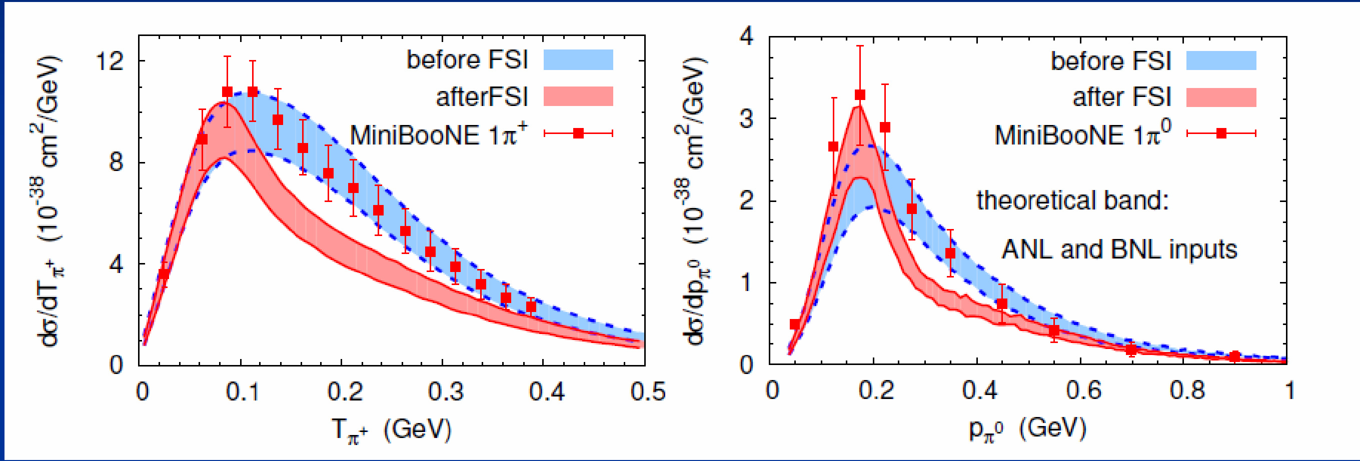
$$\mathrm{d}\sigma^{\nu A \to \ell' X \pi} = \int \mathrm{d}E \int \frac{\mathrm{d}^3 p}{(2\pi)^3} P(\mathbf{p}, E) f_{\mathrm{corr}}\, \mathrm{d}\sigma^{\mathrm{med}}\, P_{\mathrm{PB}}(\mathbf{r}, \mathbf{p}) F_{\pi}(\mathbf{q}_{\pi}, \mathbf{r}) \ .$$

Hole spectral function

$$P(\mathbf{p}, E) = g \int_{\mathrm{nucleus}} \mathrm{d}^3 r\, \Theta\left[p_{\mathrm{F}}(\mathbf{r}) - |\mathbf{p}|\right] \Theta(E) \delta\left(E - m^* + \sqrt{\mathbf{p}^2 + m^{*2}}\right)$$

Pion fsi (scattering, absorption, charge exchange) handled by transport,
Includes Δ transport, consistent width description of Delta spectral function,
detailed balance

MiniBooNE Pions



Lower border of red band: ANL input with fsi, experiment significantly higher than theory

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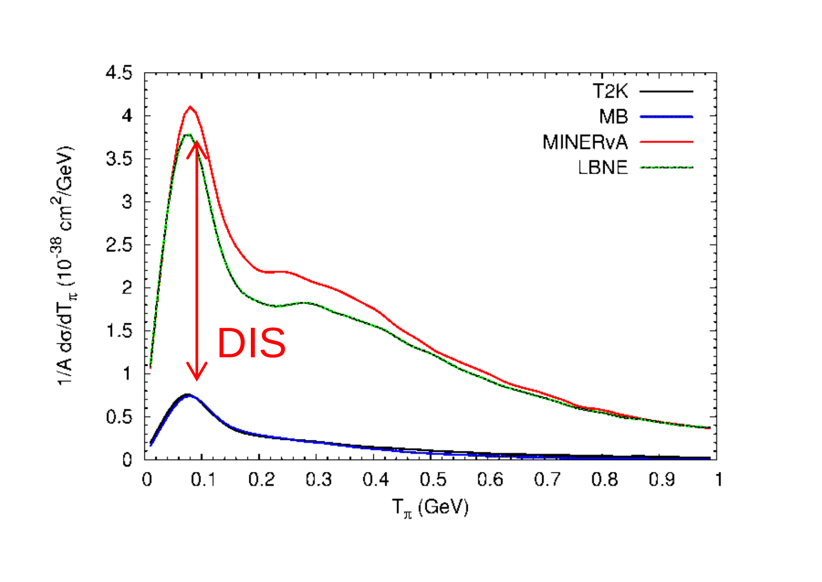
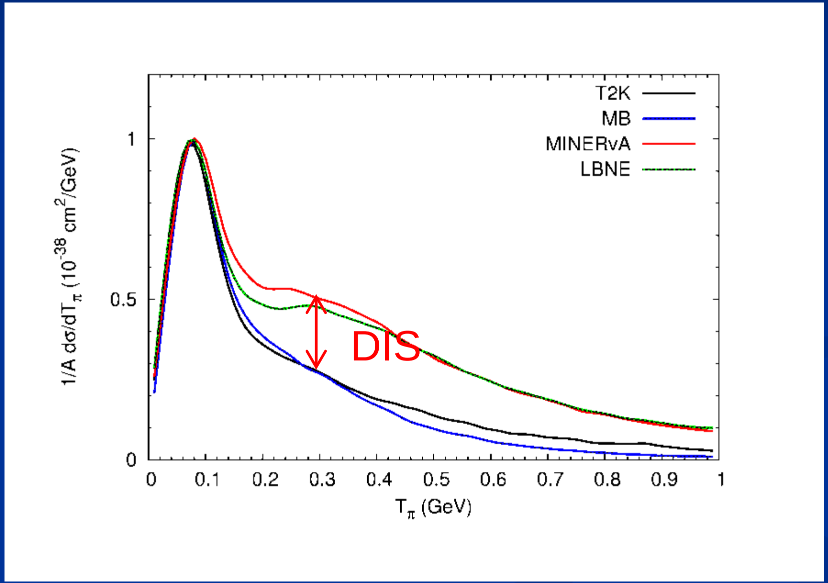
Pions at various experiments

absolute

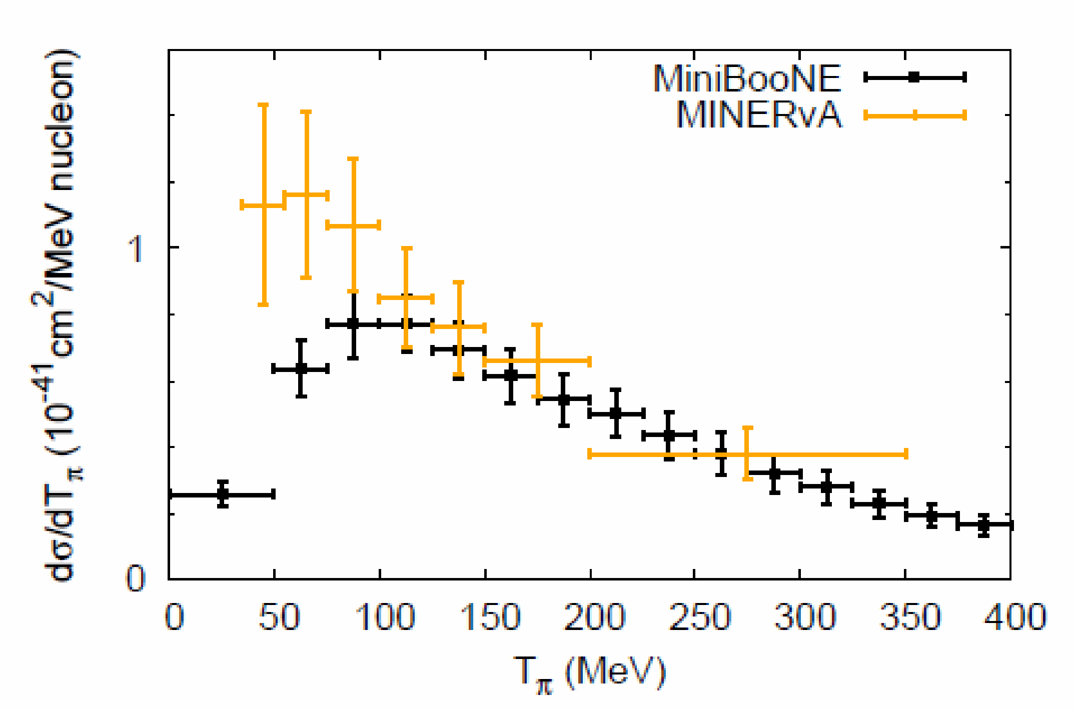


shape



Multi π^+, target: C for MB, T2K and MINERvA, Ar for LBNE

MINERvA – MiniBooNE single π data comparison

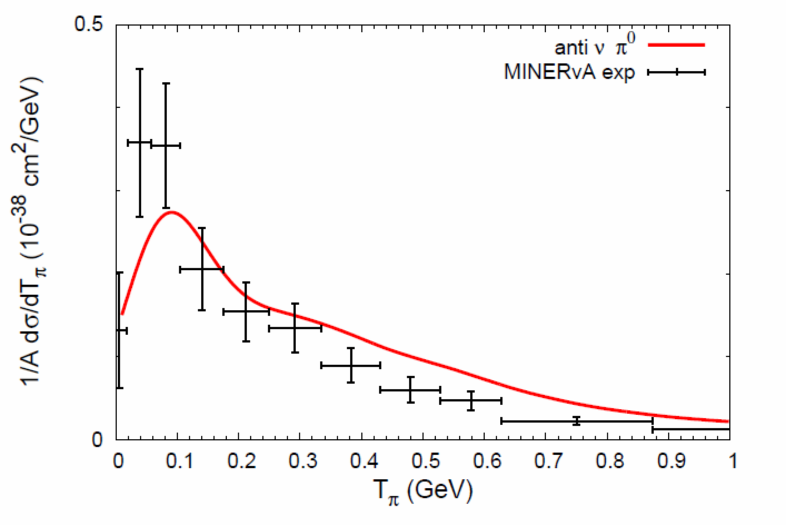


W < 1.4 GeV cut on MINERvA data

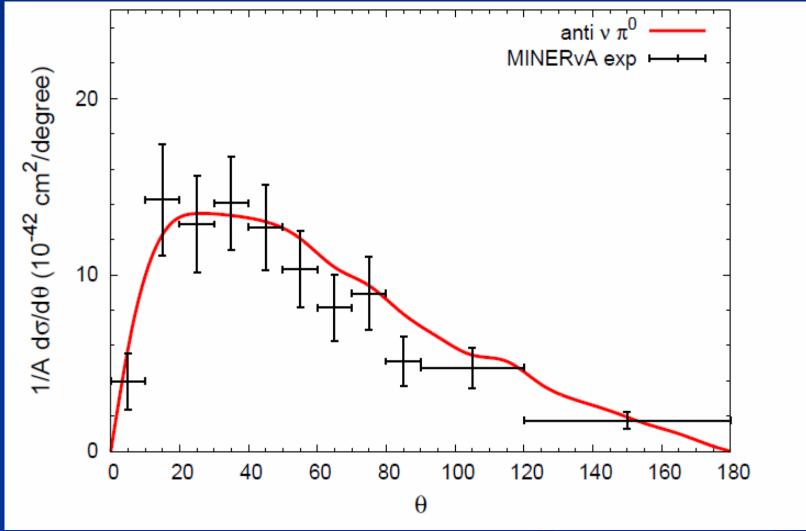
Theory gives MINERvA 1.6 × MiniBooNE

From:
Sobczyk and Zmuda, PRC 91(2015) 045501

MINERνA CC π^0 production



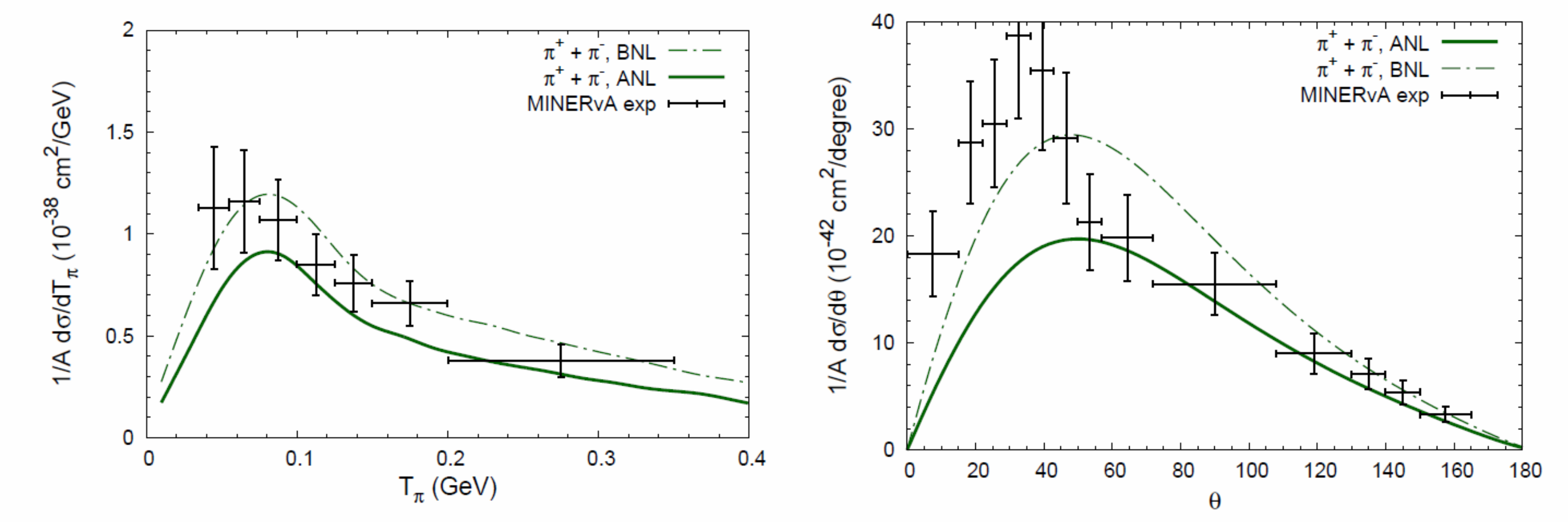
U. Mosel: arXiv:1502.08032 ,PRC



No coherent production in this channel

MINERvA CC charged Pions

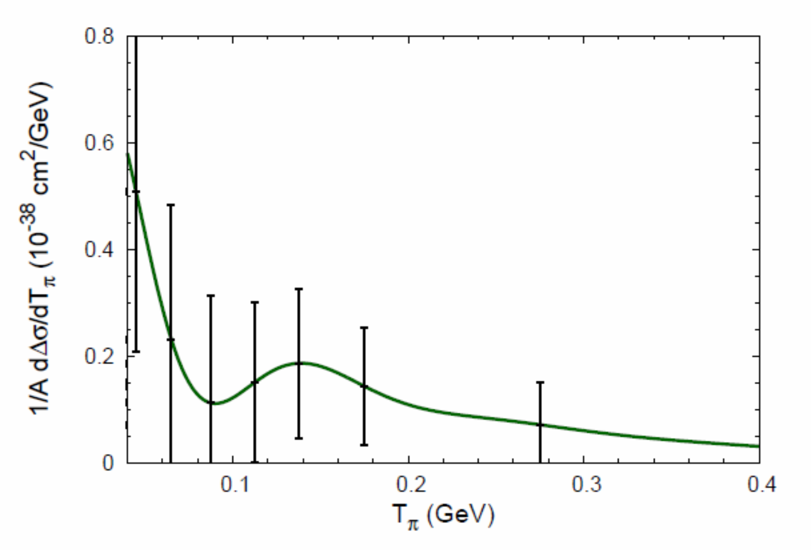
U. Mosel: arXiv:1502.08032 ,PRC

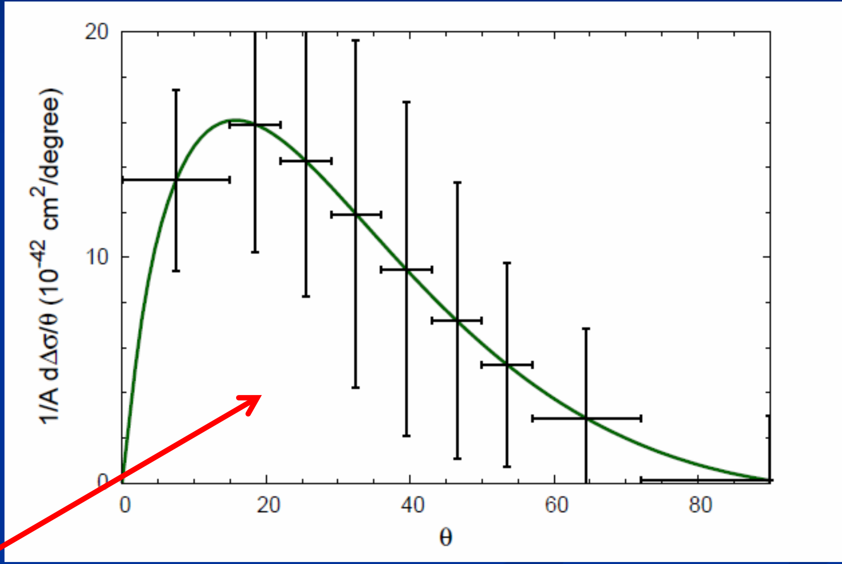


Discrepancy at low energies comes from forward angles < 50 degrees

Exp - GiBUU

U. Mosel: arXiv:1502.08032 ,PRC





Discrepancy forward peaked --› Coherent?

Integrated $\sigma = 1.9 \times 10^{-39}$ cm^2

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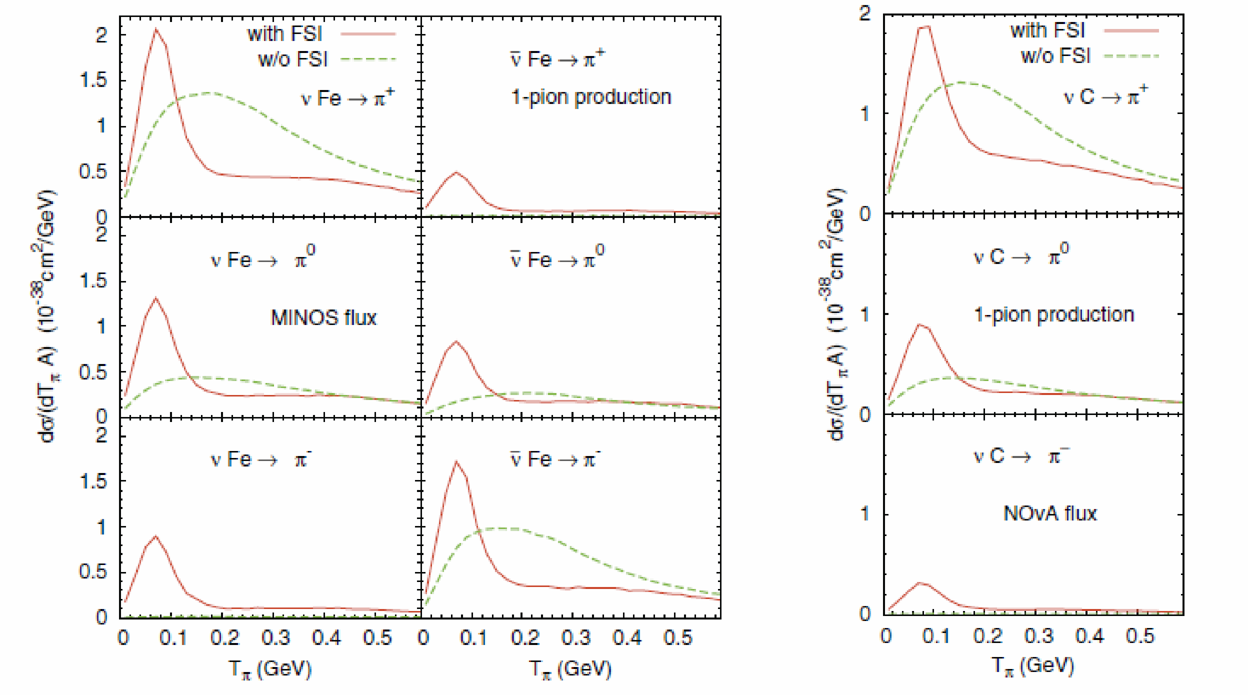
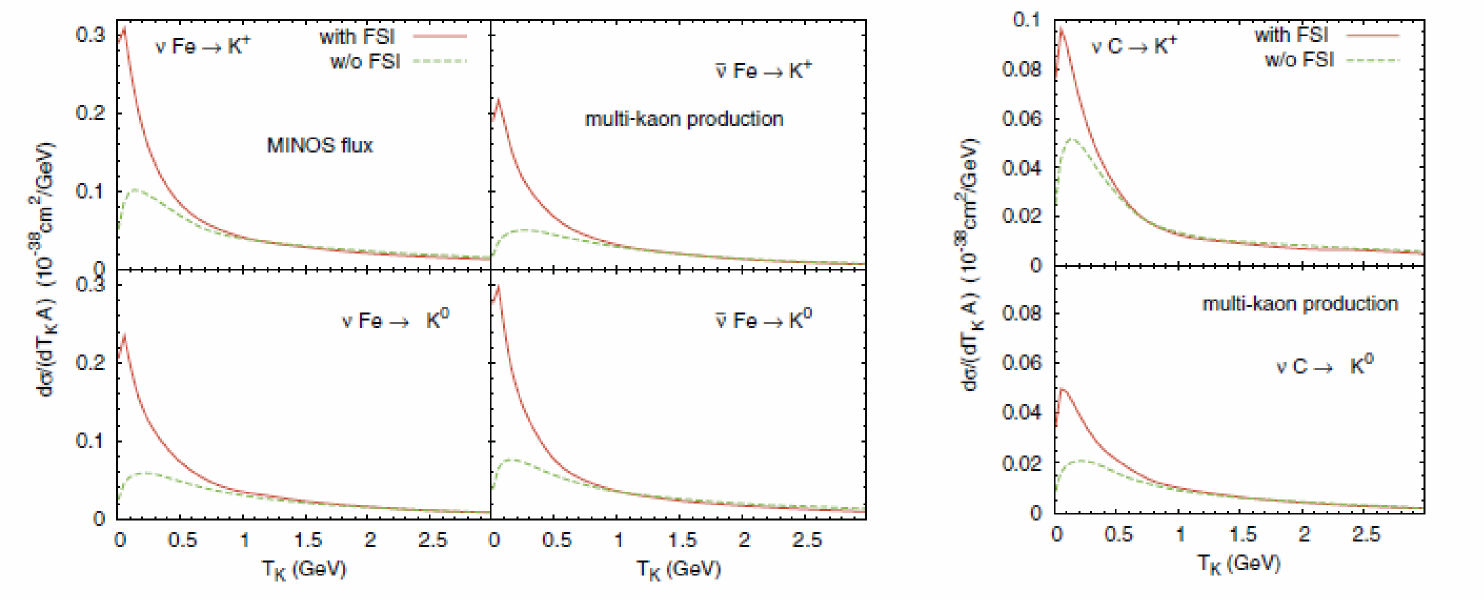
Pions at MINOS and NOvA



At higher energies pion reab-sorption reduced

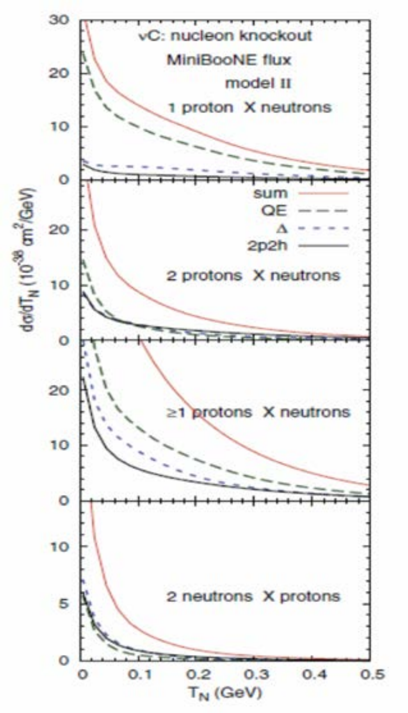
Shape dominated by FSI: seen in photo-pion production

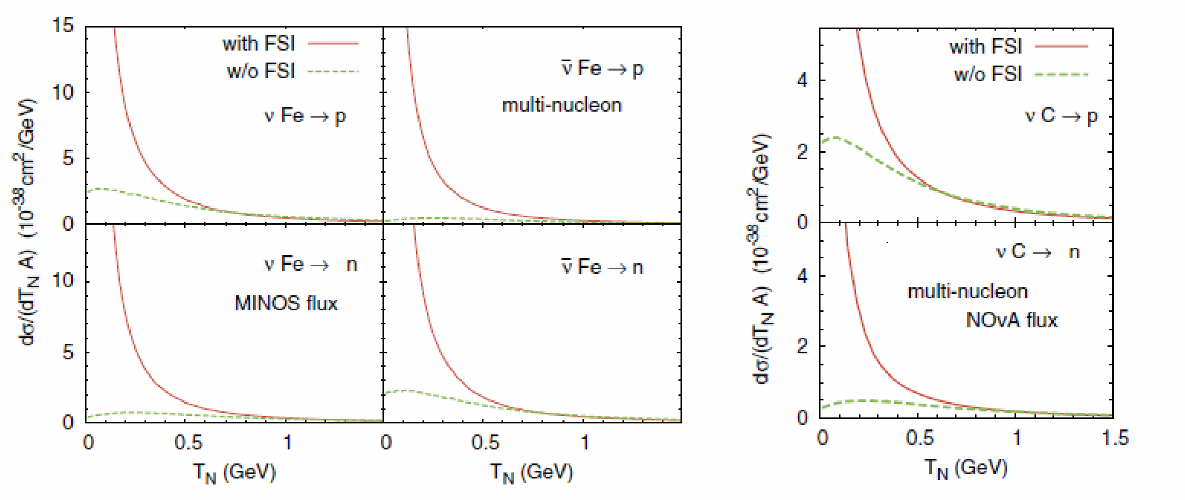
Kaons at MINOS and NOvA



FSI increase cross section!!!:: Secondaries

Knock-out Nucleons





0 pi, 1p, Xn comes close to true QE

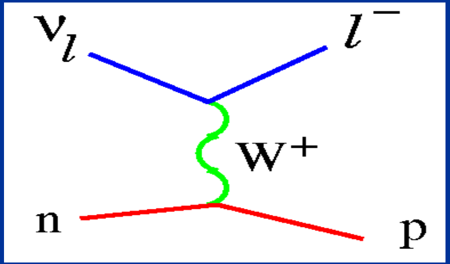
Now Energy Reconstruction through QE

- Calorimetry: Need acceptance filter to be provided by experimental groups

- QE based method

Energy Reconstruction by QE

- In QE scattering on nucleon at rest, only l +*p*, ***no*** π, is outgoing. lepton determines neutrino energy:

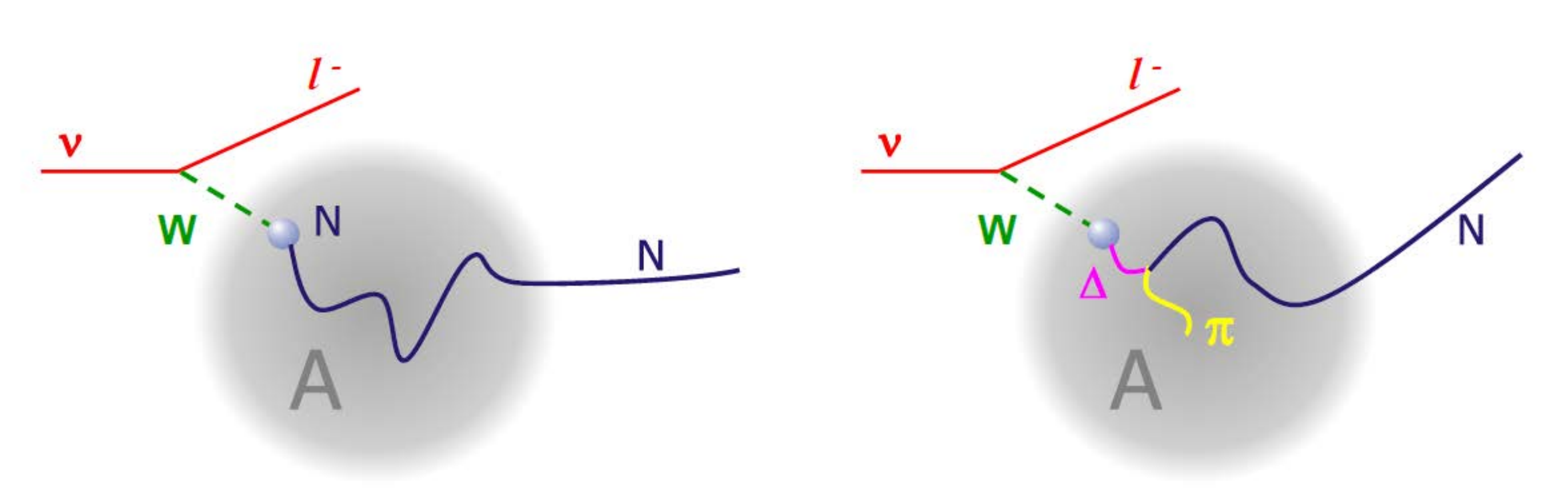


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

1. Nucleons are Fermi-moving
2. Final state interactions may hinder correct event identification

FSI in Nuclear Targets



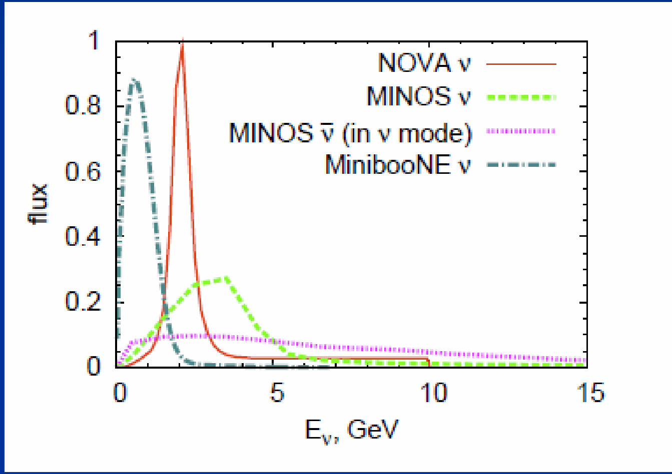
Complication to identify QE, **always** entangled with π production

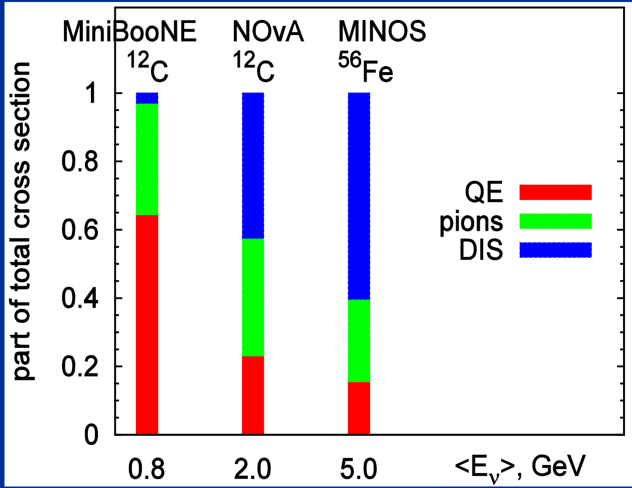
Both must be treated at the same time!

‚pure' QE cannot be measured!!

Neutrino Beams

- Neutrinos do not have fixed energy nor just one reaction mechanism





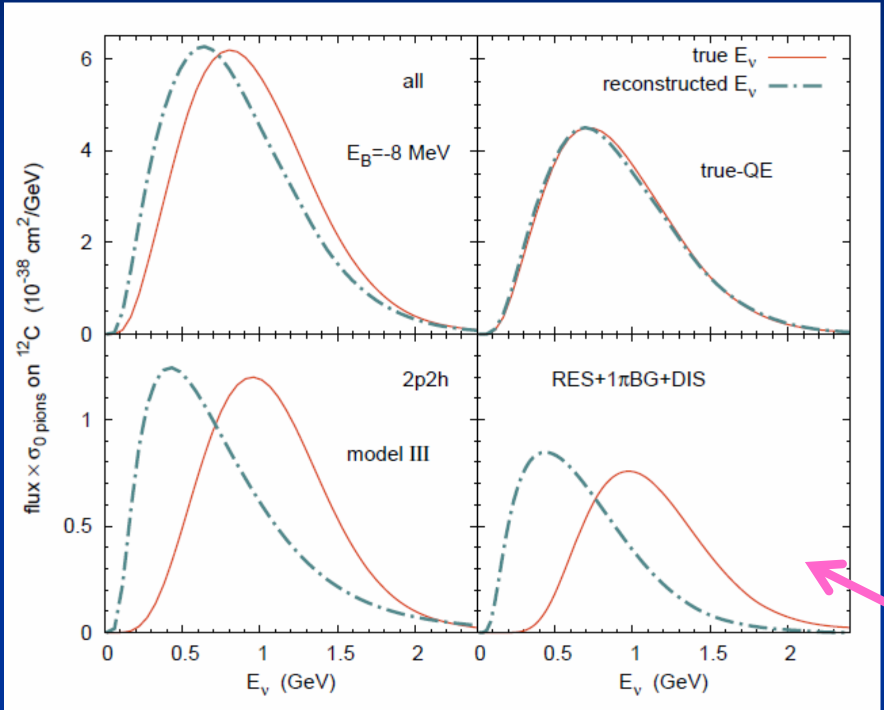
Have to reconstruct energy from final state of reaction
Different processes are entangled

GiBUU is Nature

1. Generate millions of events with GiBUU
2. Analyze them as real data, reconstruct energy
3. Compare true with reconstructed energies and Q^2

Energy reconstruction in MB

Event rates = flux x crosssection



MiniBooNE flux

Reconstructed energy shifted to lower energies for all processes beyond QE

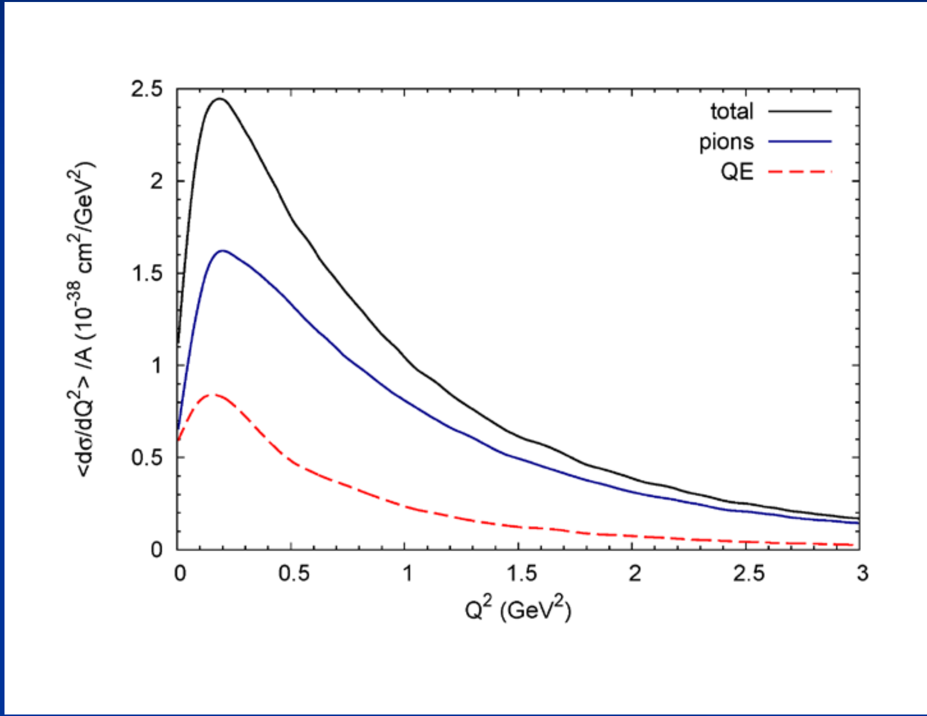
Reconstruction must be done for 0 pion events

Not only 2p-2h important

NOT contained in Nieves model

QE vs. Pion Production at DUNE

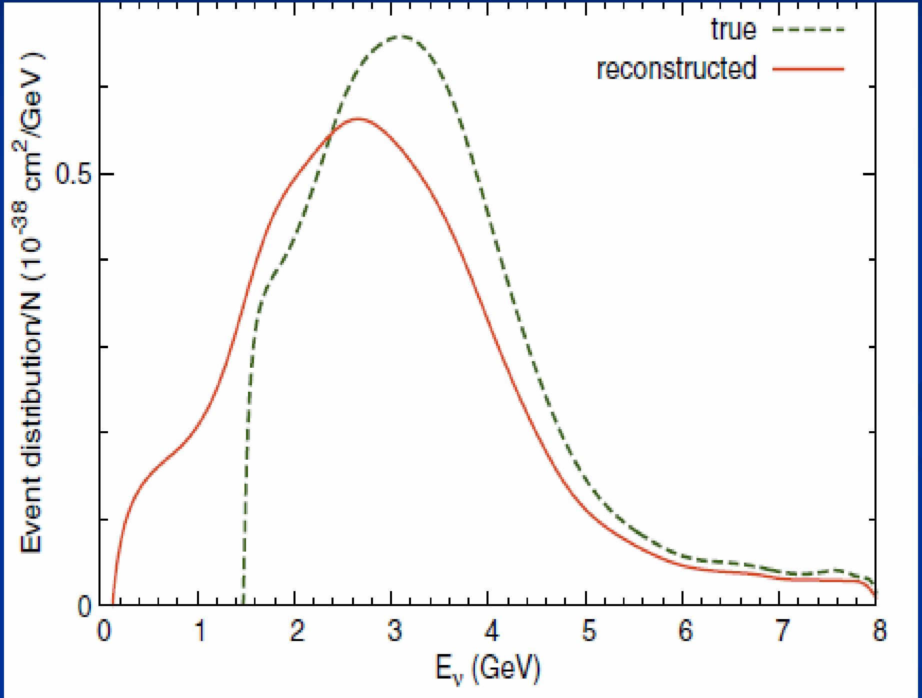
Target:
^{40}Ar



Pions: Resonance + DIS
QE: ‚true‘ QE + 2p2h

QE $\simeq$ 1/3 total
Pions $\simeq$ 2/3 total

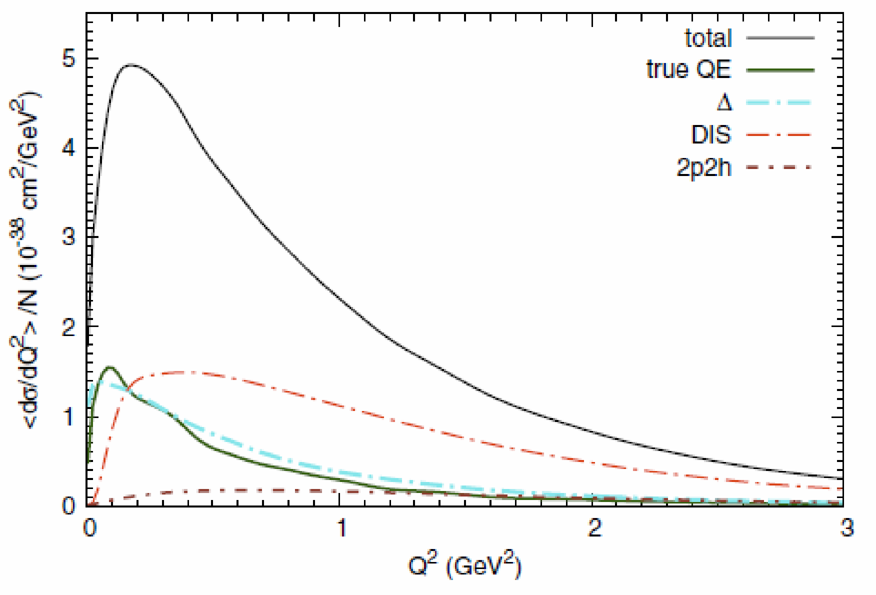
MINERvA Analysis



Flux cuts can be done only on reconstructed fluxes
mimick final state acceptance with incoming cut

Better:
final state acceptance filters

Minerva Q^2 Reconstruction



True Q^2 distribution, *all* events

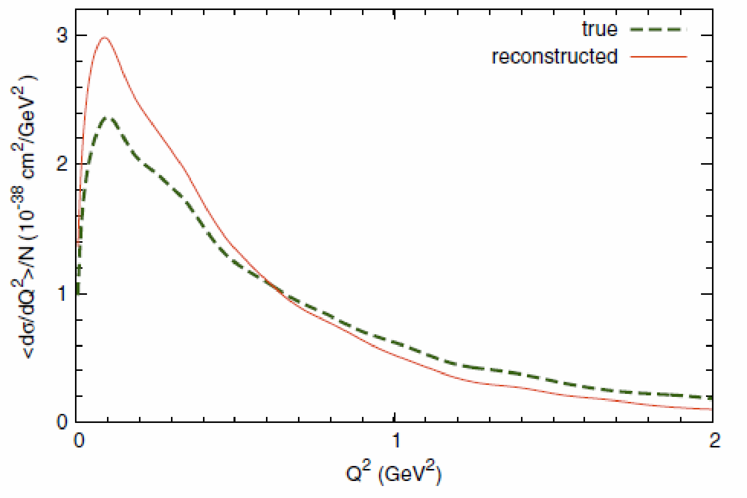
Dominant:
QE, DIS, Δ

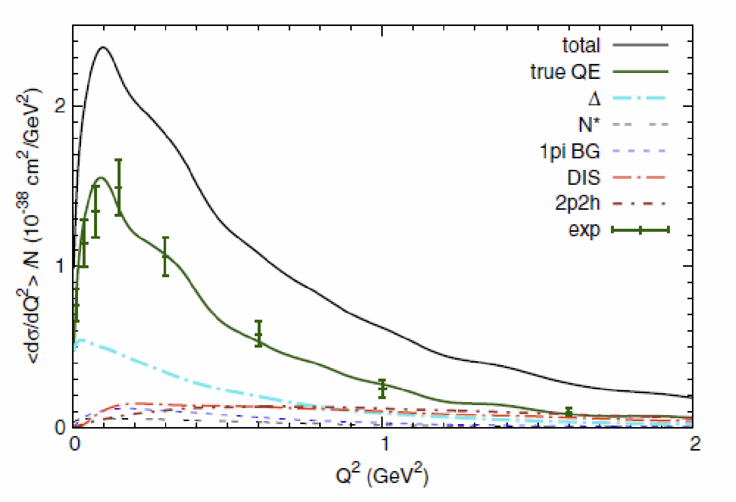
Δ and true QE very similar,
difficult to separate

Mosel et al.,
PR D89 (2014) 093003

MINERvA Q^2 Reconstruction

Only 0-pion events



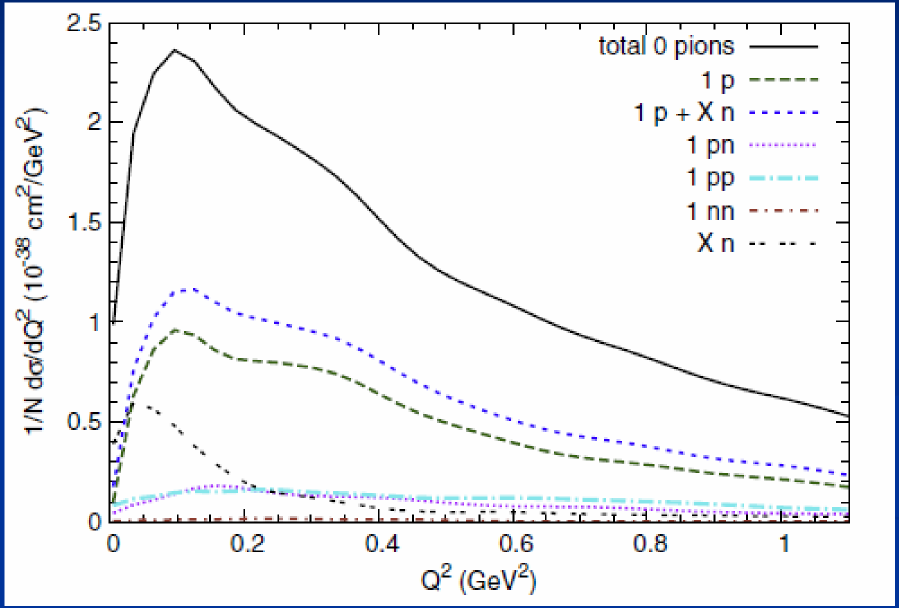


Dramatic sensitivity to reconstruction in peak area: accuracy of ‚data'??

Mosel et al.,
PR D89 (2014) 093003

Institut für Theoretische Physik
Justus-Liebig-Universität Giessen

MINERvA Q^2 Reconstruction

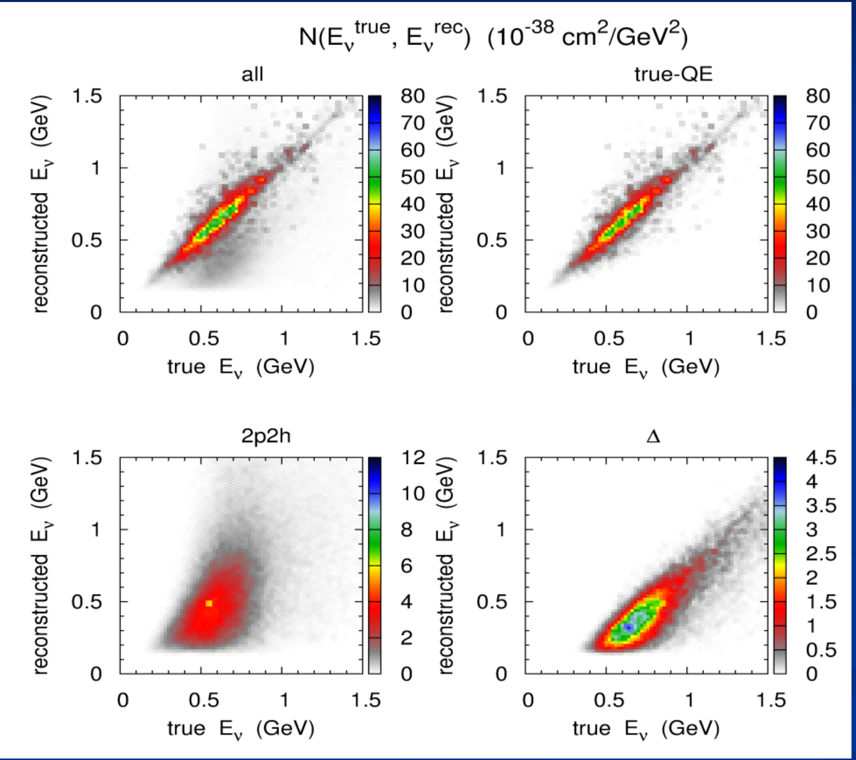


0-pion events only

Mosel et al.,
PR D89 (2014) 093003

Effects on Oscillations

T2K migration matrix

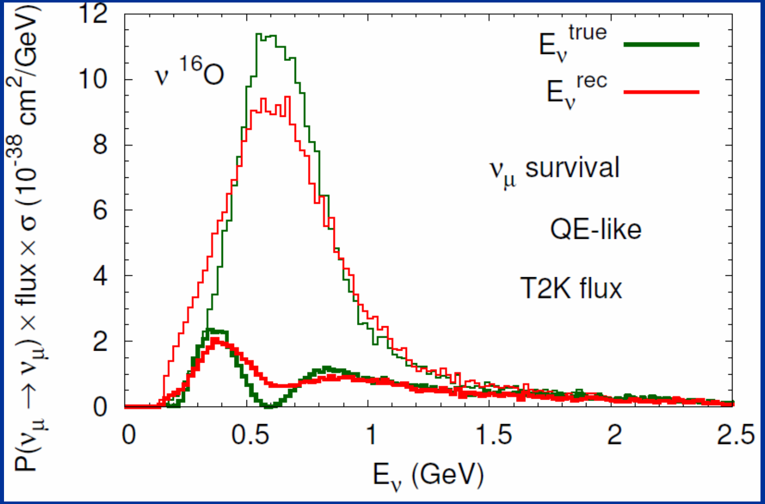


T2K Flux

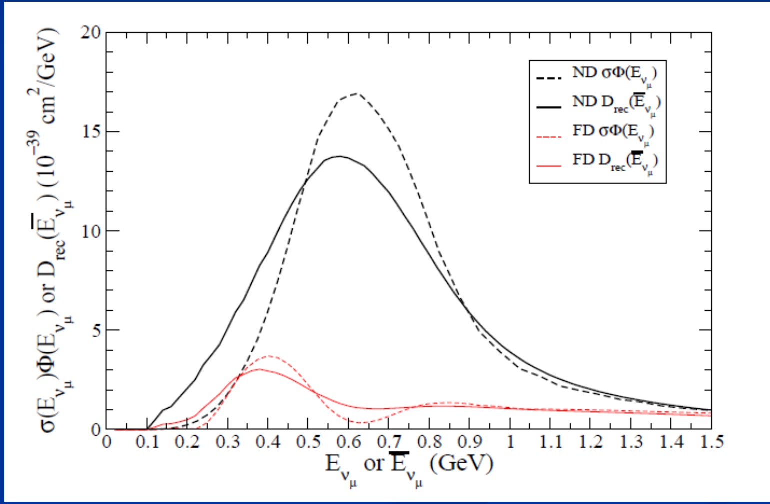
Target: ^{16}O

Oscillation signal in T2K

ν_μ disappearance

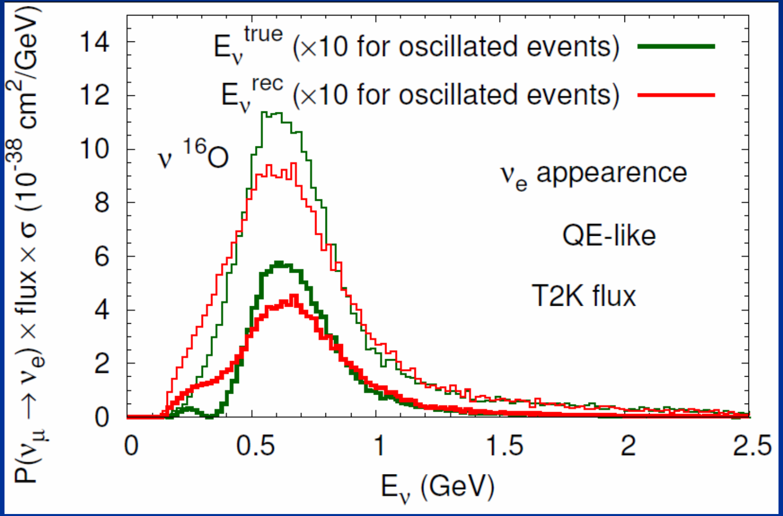


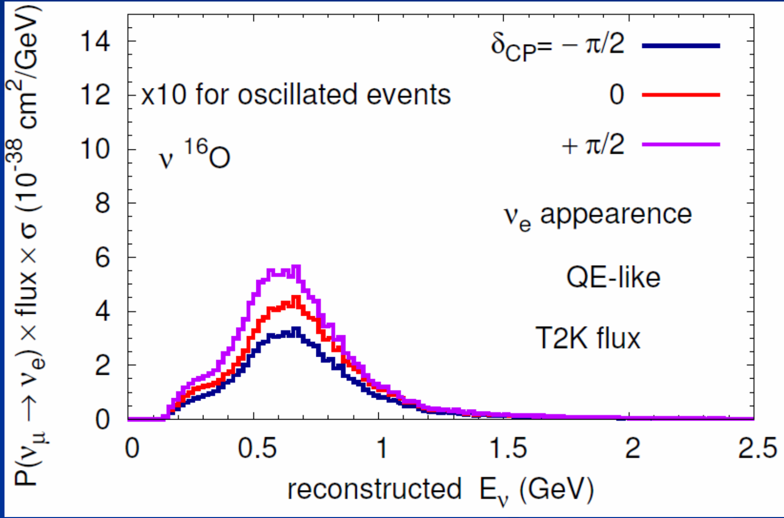
GiBUU



Martini

Oscillation signal in T2K
δ_{CP} sensitivity of appearance exps

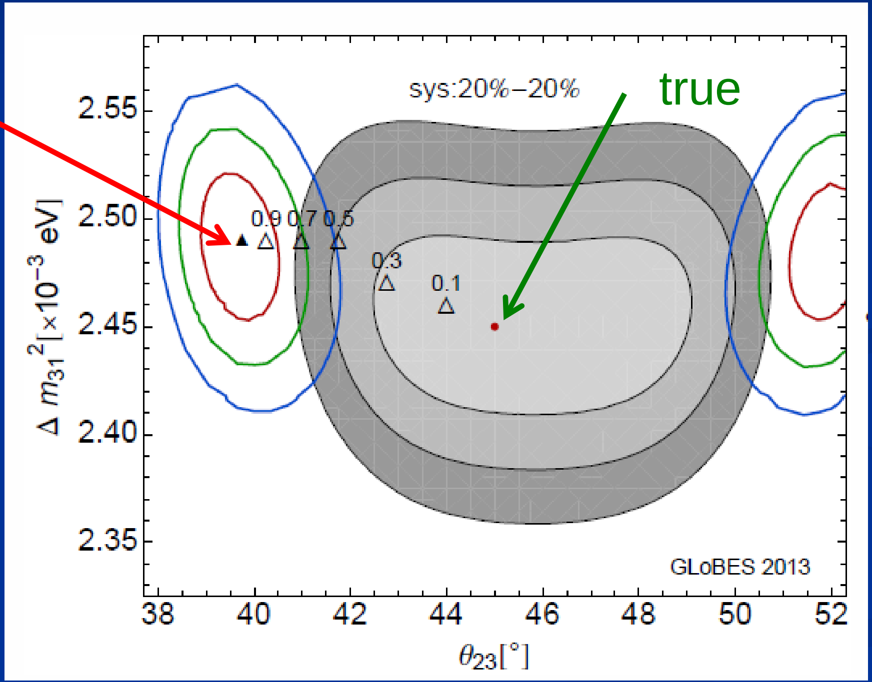




Uncertainties due to energy reconstruction as large as δ_{CP} dependence

Sensitivity of oscillation parameters to nuclear model

reconstructed from naive QE dynamics



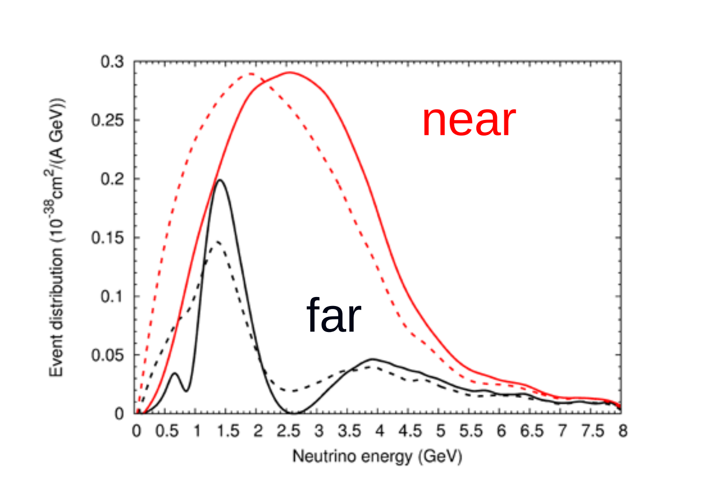
P. Coloma, P. Huber,
arXiv:1307.1243, July 2013

Analysis based on GiBUU

T2K

QE Energy Reconstruction for DUNE

Muon survival in 0 pion sample



Dashed: reconstructed,
solid: true energy

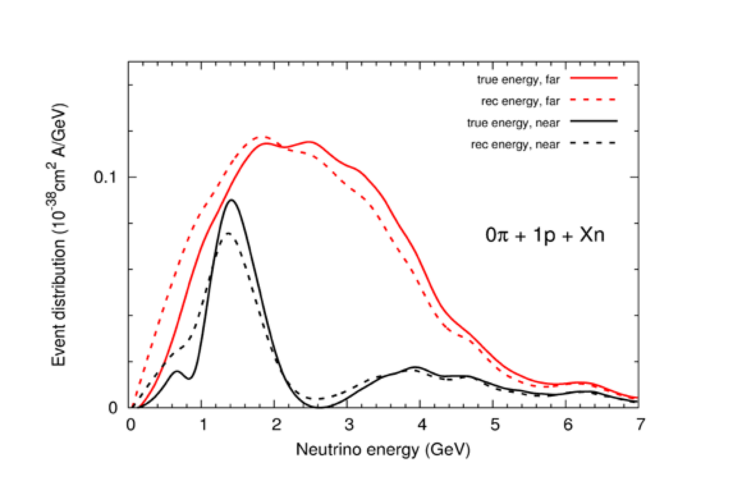
All calculations from GiBUU

Mosel et al., Phys.Rev.Lett. 112 (2014) 151802

Nearly 500 MeV difference between true and reconstructed event distributions → not a useful method

QE Energy Reconstruction for DUNE

Muon survival in 0π + 1p + Xn sample

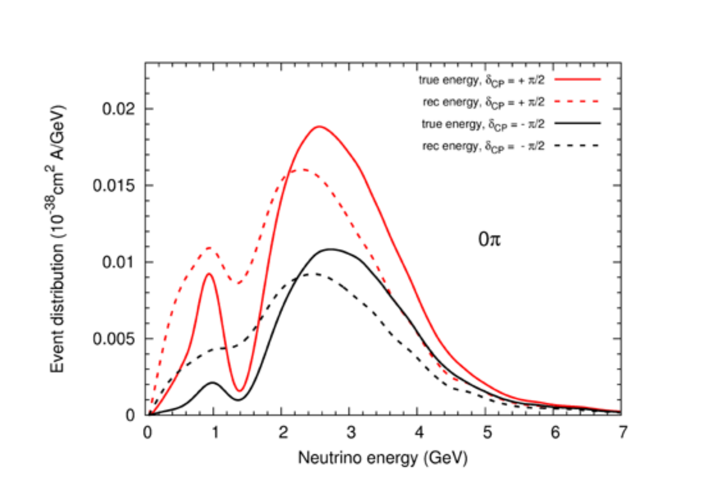


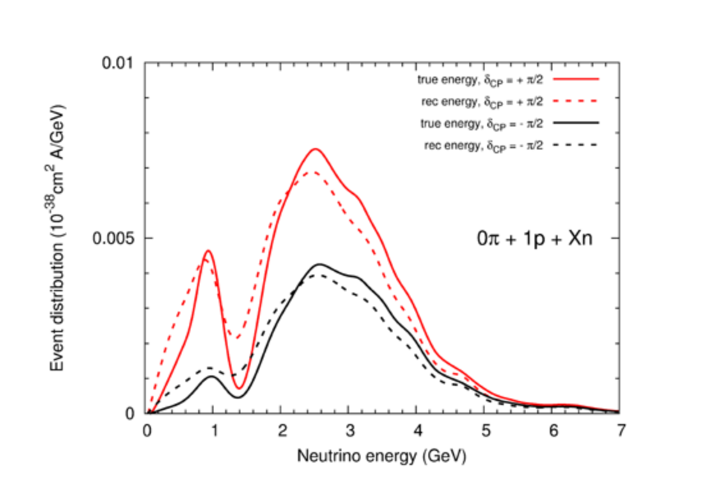
Dashed: reconstructed,
solid: true energy

Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3

DUNE *e*-appearance

Sensitivity to δ_{CP}





Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3

Summary

- Experiments with nuclear targets see QE, pion production, DIS *and* true many-body processes
- QE, pion, DIS and 2p2h can experimentally not be separated from each other → Need generator

- Precision era experiments require precision era (new) generators, open source with detailed documentation of physics and numerical methods

What is needed?

- Need reaction studies on *nuclear targets* (MINERvA, ArgoNeut, ..) to control many-body effects and fsi
- Need data without ‚generator contamination':

  e.g.: no flux cuts, no W cuts, no special reaction mechanism
- Need theory for full events, not just fully inclusive.
- Need a dedicated theory support program and a computational physics effort to construct a new, reliable generator for the precision era of neutrino physics